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NBS ULTRAVIOLET RADIOMETRIC STANDARDS

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A brief review of the standard sources and detectors available as services from NBS will be given. Emphasis will be on the use of such standards to calibrate the radiant power of unknown sources or the response of radiation detectors and spectral radiometers at wavelengths less than 400 nm. The following standards, listed in order of decreasing wavelength, are or will soon be available: the tungsten filament quartz-halogen lamp (above 250 nm); the tungsten strip lamp (above 225 nm); the low pressure mercury vapor lamp (253.7 nm); the deuterium arc lamp (165 to 350 nm); the argon "mini-arc" (115 to 400 nm); photodiode detectors (20 to 254 nm); and the synchrotron radiation source, SURF-II (5 to 400 nm). The relative strengths and limitations of these radiometric standards with respect to accuracy, reliability, convenience, and intensity and wavelength range will be discussed.

(Ultraviolet, Radiometry, Standards, NBS, Sources, Detectors, Survey)

Introduction

In the wavelength region between 5-400 nm, NBS offers a variety of standard sources and detectors which may be used to calibrate the radiant power of unknown sources or the response of radiation detectors and spectral radiometers. A brief review of the available services will be given and in addition several current projects which are meant to improve the accuracy, performance and variety of ultraviolet radiometric standards will be mentioned.

The ultraviolet wavelength region can be considered to extend from 400 nm, the near ultraviolet, to about 4 nm where the soft x-ray region begins. For perspective some key wavelengths in this region are illustrated in figure 1. The critical atmospheric ozone absorption occurs between 200-280 nm, the so-called UVC region. The UVA and UVB regions define the regions 315-400 nm and 280-315 nm respectively. Molecular oxygen absorption characterizes the region below 200 nm and thus the terminology "vacuum ultraviolet" to indicate the necessity for the absence of air in a measurement system designed to detect or utilize such radiation. Atomic hydrogen absorption sets in at 100 nm and sets a limit to the range of interstellar astrophysical measurements. However, the real importance of the ultraviolet wavelength region is contained in the energy scale corresponding to the wavelength scale in figure 1. The ultraviolet energy range spans from about 3 eV to 300 eV, which is quite large as compared to the visible, for example, which extends only from 1.5 eV to 3 eV. This energetic radiation can be used to drive and control all sorts of chemical and biological reactions. For example extreme doses can cause skin cancer; controlled doses can heal. Continuous exposure to ultraviolet radiation causes the fading of paints and dyes; controlled exposures in specific processes are used to produce protective coatings on materials. Some documented examples of the various applications of ultraviolet radiation as both a natural and artificial element in our home and work environment are shown in Table 1.

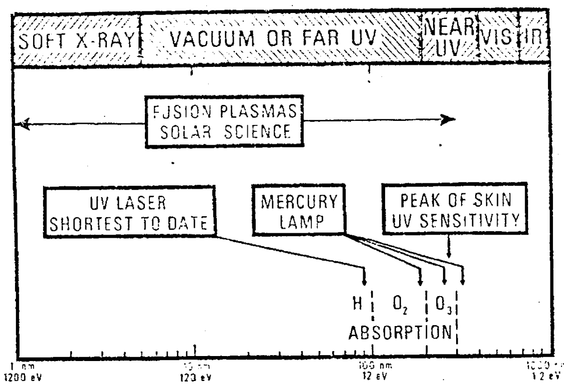

Figure 1. The ultraviolet region of the electromagnetic spectrum defined in terms of wavelength (nm), energy (eV) and some key processes.

Photochemistry
Thin film production
Tooth decay prevention
Textile dyes
Paint curing
Industrial finishes
Cast hardening
Instant oscillographs
Material degradiation
UV photosensitive paper
Counterfeit money detection

Bacteriological
Germicidal lamps in hospitals, schools, and offices
Germicidal lamps in industry

Environmental Studies
Atmospheric sciences
Ecology and the ozone layer
Oil spill identification
Water purification
Water pollution
Smog Gauge

Medical and Therapeutic
Jaundice treatments
Calcium deficiency
Skin disease treatments
Wrinkling
Drug detection
Medical research

Fusion Research
National controlled thermonuclear fusion efforts

Space Science
Communications
Astrophysics
Skylab
Space shuttle
Reentry and rocket exhaust

VUV and X-Ray Lasers
Integrated circuits
Plasma probes
Isotope separation
Molecular synthesis
High resolution holography
Tumor therapy
Laser fusion

Photobiology
NBS benchmark experiments

Plasma Chemistry
Thin film deposition
Plasma arc steel furnace
Recycling of alloys in steel production

Table 1. List of applications requiring ultraviolet radiation measurements.

Why are accurate radiant power measurements needed in these areas and how does NBS interact with the measurement system? Basically, in three ways: (a) on the research level--new techniques require accurate documentation for the process or procedure to gain widespread commercial acceptance; (b) on the sales level--commercially available products need standards in order to meet specifications and to compete on a national and international market; and (c) on the applications level--the user needs standards in order to check specifications, to maintain quality control, and to monitor the health and safety of workers. As an example of these impacts, consider an industrial assembly line process in which certain manufactured items like paper products, glass, metal parts, microcircuits, or textiles are being coated by radiation curing. (a) For the uv radiation curing technique to be accepted in the first place, it would have to be well understood so that performance could be guaranteed. (b) The equipment which would enable the assembly line to operate at the highest speed is the most desirable (maximum ultraviolet flux in the most effective bandpass). (c) Periodic calibrations in the field are necessary to accurately monitor the intensity of bands of uv radiation hazardous to employees and to measure possible deterioration of the equipment due to radiation damage of the optical components.

Radiometric Quantities

In general, there are two ways to determine the radiant power of an unknown light source: (a) through the use of standard sources and (b) through the use of standard detectors. Standard sources are most useful when it is desired to know the emission characteristics of an unknown source. Standard detectors are most useful, on the other hand, when it is desired to know the radiant power at the location of a detector. For example, if the quantity of interest is spectral radiance [watts cm^{-2} nm^{-1} sr^{-1}], that is, if one is concerned with the power *radiated* by a specified emitting surface (cm^2) in a certain wavelength band (nm) at a given solid angle (sr), then the light source to be investigated as well as the standard source may be set up in such a manner that the radiation from both passes through the same optical-spectrometric arrangement, thereby eliminating all geometric and other specific factors of the instrumentation. In short, the calibration is effected by a simple substitution of sources in the experimental arrangement. On the other hand, if the quantity of interest is spectral irradiance [watts cm^{-2} nm^{-1}], that is if one is concerned with the radiant power *incident* on a specified surface area (cm^2) in a certain wavelength band (nm), then ideally a standard detector and filter arrangement is placed at the location of the irradiated surface to measure the power. Alternatively, if such a standard radiometer is not available, a standard source of spectral irradiance may be used in conjunction with a suitable diffusing element (to account for variations in the geometries of the standard and the unknown sources) to determine the response function of the user's diffuser-radiometer system.

At NBS, standard sources of both ultraviolet spectral radiance and spectral irradiance are available. In the case of NBS standard detectors for the ultraviolet, the calibrated quantity is the absolute quantum efficiency [photoelectrons per incident photon] as a function of wavelength.

Standard Sources

The three primary source standards being used at NBS are the gold point blackbody cavity for which the spectral radiance is given by Planck's law, the wall-stabilized hydrogen arc for which the spectral radiance is given by accurately known quantum mechanical absorption coefficients for atomic hydrogen, and the electron storage ring facility for which the spectral radiance is given by the theory of electron synchrotron radiation. The selection of one of these standards for a calibration application is influenced mostly by the specified wavelength region.

The primary standards are most often used to calibrate secondary or transfer standards of spectral radiance which can then be issued to customers. The secondary radiance standards are also used to generate spectral irradiance standards. The following ultraviolet standard sources, listed in order of decreasing wavelength, are available from NBS: the tungsten filament quartz-halogen lamp (above 250 nm); the tungsten strip lamp (above 225 nm); the low pressure mercury vapor lamp (253.7 nm); the deuterium arc lamp (165 to 350 nm); the argon "mini-arc" (115 to 400 nm); and the synchrotron radiation source, SURF-II (5 to 400 nm). The relative strengths and limitations of these radiometric standards with respect to accuracy, reliability, convenience, and intensity and wavelength range will now be discussed.

(1) Tungsten Lamps

Tungsten strip lamps are used as transfer standards of spectral radiance, and tungsten quartz-halogen lamps are used as transfer standards of spectral irradiance. The tungsten resistive element is heated to incandescence by a specified dc electric current. Power requirements are about 8 A @ 110 V for the irradiance standard and about 50 A @ 15 V for the radiance standard. Between 400 and 250 nm, the spectral distribution of the quartz-halogen lamp and the tungsten strip lamp is approximately that of a 3000 K and 2700 K blackbody respectively.

Strengths: Techniques are well understood and calibrations based upon the conventional blackbody cavity are possible with uncertainties on the order of 1-3 percent.

Limitations: Relatively weak sources in the ultraviolet, especially below 250 nm where the application of these sources is limited by both low signal levels and significant scattered visible light. For example, the spectral radiance of a tungsten strip lamp at 230 nm is about 1000 times lower than it is at 400 nm.

(2) Low Pressure Mercury Vapor Lamps

The irradiance of the 253.7 nm resonance line of mercury can be measured for various types of low pressure lamps supplied by the customer. The approximate uncertainty is 5% for irradiance levels on the order of 0.5 to 30 $\mu W\ cm^{-2}$.

Strengths: Calibration technique utilizes quartz-halogen spectral irradiance standard and can be extended to other line sources in the region above 250 nm.

Limitations: The calibration of the customer's lamp is only as good as its stability and reproducibility.

(3) Deuterium Arc Lamps

These are available as transfer standards of spectral radiance (165-350 nm) and irradiance (200-350 nm) with calibration uncertainties of about 10%. A short L-shaped arc discharge is formed between two electrodes set at 90° in the sealed lamp and excites a molecular D_2 continuum. The low pressure deuterium lamp spectrum peaks at about 200 nm where the spectral irradiance of a typical 30 W lamp is about 100 times greater than that of a 1000 W quartz-halogen lamp. Calibrations are based upon the hydrogen arc primary standard of spectral radiance. Irradiance calibrations have just recently become available down to 200 nm. Plans are to extend this service down to 165 nm.

Strengths: Very strong ultraviolet output, portable, low power requirements.

Limitation: Alignment is difficult, and there are uncertain long-term aging effects.

(4) Argon Mini-Arc

The mini-arc is a one atm pressure wall-stabilized arc discharge operated at power levels up to 1.5 kW depending upon the intensity desired. The spectrum is line-free between 194 and 350 nm and interrupted by only a few very narrow air impurity lines between 114 and 194 nm. The spectral radiance of the argon continuum is determined in the region 114-350 nm by comparison with the hydrogen arc primary standard. The mini-arc has just recently become available. Future plans are to determine its suitability as a far ultraviolet spectral irradiance standard.

Strengths: Continuum is intense (a factor 1000 stronger than the tungsten strip lamp at 250 nm), lamp aging is negligible, the uv wavelength coverage is the most extensive of all transfer lamps, and the alignment procedure is more reliable than for the deuterium lamp.

Limitations: The lamp system and ignition procedure are slightly more complicated than those previously described; not commercially available.

(5) Synchrotron Ultraviolet Radiation Facility (SURF-II).

The theory of synchrotron radiation from accelerated electrons is on excellent theoretical grounds, and the continuum emission can be quantitatively predicted when the energy of the electrons, the radius of the orbiting electrons, and the electron current are known. The radiation beam from the NBS 240 MeV storage ring is highly collimated, polarized, and intense, on the order of 10^{11} photons $s^{-1}nm^{-1}mrad^{-1}$ in the wavelength range 10-400 nm. Uncertainties in the flux determination are expected to be in the 5 to 10% range. There are no plans at present to calibrate transfer sources with the synchrotron radiation, but rather guests are invited to use the facility for their own purposes. Efforts are currently being made to organize and streamline the procedures so that such a collaboration can be carried out most efficiently.

Strengths: An intense source of continuum radiation which covers the entire visible and ultraviolet region.

Limitation: Major facility, high vacuum requirements, guest worker arrangements must be made.

Standard Detectors

The primary standard for detector calibrations at NBS is a double-ionization chamber, a gas-filled detector in which each photon absorbed produces one electron-ion pair which is collected by a simple arrangement of parallel plates used to set up the collecting field. The transfer to the actual photodiodes which are available to customers is accomplished through the use of a uniformly grey (percent of radiation absorbed is independent of wavelength) thermopile whose efficiency has been calibrated with the ionization chamber at short wavelengths and checked with a spectral irradiance standard source at 253.7 nm. Windowed photodiodes calibrated in this manner have been used to evaluate the response of other detectors such as photomultipliers, and the response of radiometers such as "hazard meters" which are designed to have a spectral response equivalent to a specified erythemal curve.

(1) Window Photodiodes

This transfer standard is basically a vacuum photodiode in which ideally the only parameter to be determined by reference to an absolute standard is the absolute photoelectric yield of the photocathode as a function of wavelength. The detectors are evacuated and sealed by an ultraviolet transmitting window to avoid atmospheric contamination of the surfaces. Calibration uncertainties are estimated to be about 6%. The uniformity of the quantum efficiency of the cathode can be excellent, on the order of 1 percent. Aging effects are likewise negligible.

(2) Windowless Photodiodes

Basically this is the same type of detector as described above, but the lack of a window and the consequent occasional exposure of the photocathode to laboratory conditions affects the overall reproducibility. Nevertheless, there is evidence that natural aging effects cause not more than a 20 percent change in quantum efficiency over a three year test period.

Strengths of (1) and (2): Wide wavelength region of applicability (20 nm to 300 nm); relatively high accuracy and stability.

Limitations of (1) and (2): These are low current devices (no amplification). If they are used to calibrate more sensitive photomultipliers, linearity and scaling problems with the latter introduce additional uncertainties.

Summary

Ultraviolet standard sources and detectors are available from NBS with uncertainties in the range of 3-10% depending upon the type of calibration required and the wavelength region of interest. In certain cases, arrangements can be made to use NBS radiometric facilities; collaborative efforts are also possible. Requests for services should either be directed to the appropriate sections (232.03, 232.04, 232.07, or 232.14) or, in general, to the NBS Office of Measurement Services.

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